DEVELOPMENT OF RESIDUAL STRESS MEASUREMENT FOR CONCRETE PAVEMENTS THROUGH CANTILEVERED BEAM TESTING

By:
David G. Marks and David A. Lange
Department of Civil and Environmental Engineering
University of Illinois Urbana Champaign
Urbana, IL 61801
USA
Phone: (217) 333-4816; Fax: (217) 265-9464
marks5@illinois.edu
dlange@illinois.edu

PRESENTED FOR THE
2010 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2010

ABSTRACT

Knowledge of residual stresses is important in understanding and predicting the performance of concrete pavements. However, there is not a standard pavement test to determine these stresses. Prior pavement research was inspired by the hole-drilling strain-gage method used in metals. This method involves drilling a small hole into the specimen and measuring the resulting stress relaxation near the hole with strain gages. The strain change is then used to calculate the residual stresses in the metal. The pavement research at the Federal Aviation Administration's National Airport Pavement Test Facility showed the promise of using core rings to create a similar stress relaxation in cantilevered concrete beams. Testing at the University of Illinois continued the use of core rings and cantilevered beams and also introduced a method using notches. Strain gages on each beam measured the strain relaxation due to a core ring, one notch, or many notches. Strain relaxation was clearly seen in the core ring and notch beam tests, and this relaxation was most pronounced with the notch tests. Sawing a notch on both sides of a strain gage was able to relax all of the strain induced by the cantilever loading, making the residual stress calculation quite simple. A two-dimensional finite element analysis was used to parallel the testing and to learn more about the stress distributions in notched cantilevered beams.

INTRODUCTION

Information about the stresses in an in-place concrete pavement is useful in determining the pavement's response to the current conditions and also in predicting its future behavior. Many factors affect these concrete residual stresses such as moisture, temperature, creep, shrinkage, base conditions, and loading conditions. Direct measurement of the residual stresses is not only a straightforward means to determine the stresses, but it can also be valuable for validating numerical stress calculations.

Metal processing and machining creates residual stresses, and residual stress tests for metals have received a lot of attention, resulting in many test methods as documented by Li [1]. Research work at the FAA's NAPTF took a residual stress test originally used in metals and applied it to concrete beams. [2] The test for metals is the hole-drilling strain-gage method. In this method, strain gages measure the strain relaxation created by drilling a hole in the part. The strain relaxation and hole geometry can be used to estimate the original residual stresses. The standard for this method, ASTM E 837, uses a 0.08 in hole and similarly small strain gages. Concrete does not behave homogeneously at this scale, so the NAPTF researchers used larger strain gages and substituted a core ring for the hole.

The work presented in this paper directly branched from the NAPTF research. This project began as a validation step for the core ring strain gage method. Concrete beams were loaded as cantilevers to induce stresses and core rings were drilled near surface strain gages. The core ring test was not completely satisfying as the strain measurements were not always well-behaved, and even for a test without measurement difficulties, only a fraction of the concrete stress is relieved. The second step of this project was a switch from the core rings to notches. Sawing notches near the strain gages produced fewer measurement challengers than drilling core rings, and most notably, sawing a notch on both sides of a strain gage was able to fully remove the induced stress at the gage. This full isolation greatly simplifies the procedure for calculating the original stress.

CORE RING BEAM TESTS

Concrete beams used in this project measured 6x6x34 inches. A testing table with a hydraulic actuator was used for the cantilever loading. Steel bars were anchored to the table with threaded rods and they fixed the end of the beams from rotating, as illustrated in Figure 1. The downward force from the actuator was distributed to the top of the beam through a roller, a steel plate, and a bearing pad to prevent any localized crushing. Despite the sturdy end fixity, it was believed the fixed end would still rotate slightly due to the actuator loading; the rotation would then cloud the actuator's displacement data. A deflection bracket was bolted to the fixed end of the beam and would measure the deflection of the loaded end of the beam with an LVDT. The bracket was designed to rotate with the beam; rotations of the support would then not influence this measurement. However, the brackets used were not nearly stiff enough, and the spring force of the LVDT deflected the brackets and made these deflection measurements unreliable.

A surface strain gage was attached to the top surface of the beams, closer to the fixed end where the load-induced stresses were highest. The strain gages used in this project had gage lengths of 20 and 30 mm (0.8 and 1.2 in). After they were attached to the concrete, the gages were waterproofed by being covered with an inert sealant followed by aluminum tape. <u>This preparation was used to protect the gages from the cooling water used in the coring procedure.</u>

The coring apparatus drilled 3-in diameter core rings and required two people to operate. One person controls the attached hand drill and the other rotates the handles to advance the coring bit. The apparatus is clamped to the beam as shown in Figure 2. Water to keep the coring bit cool is pumped into the coring housing from a bucket below the table.

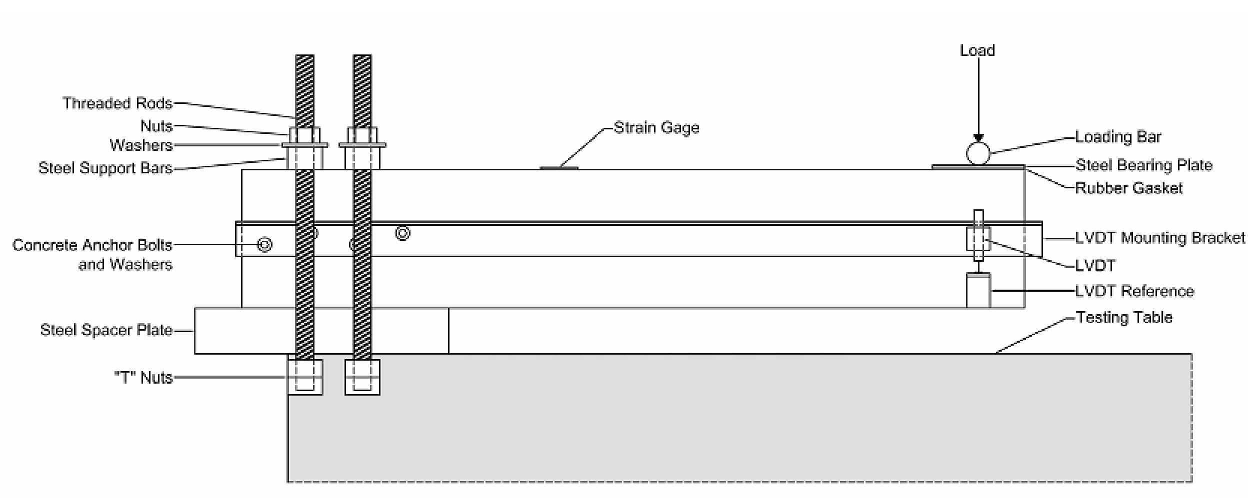

Figure 1. Drawing of the cantilevered beam test setup.

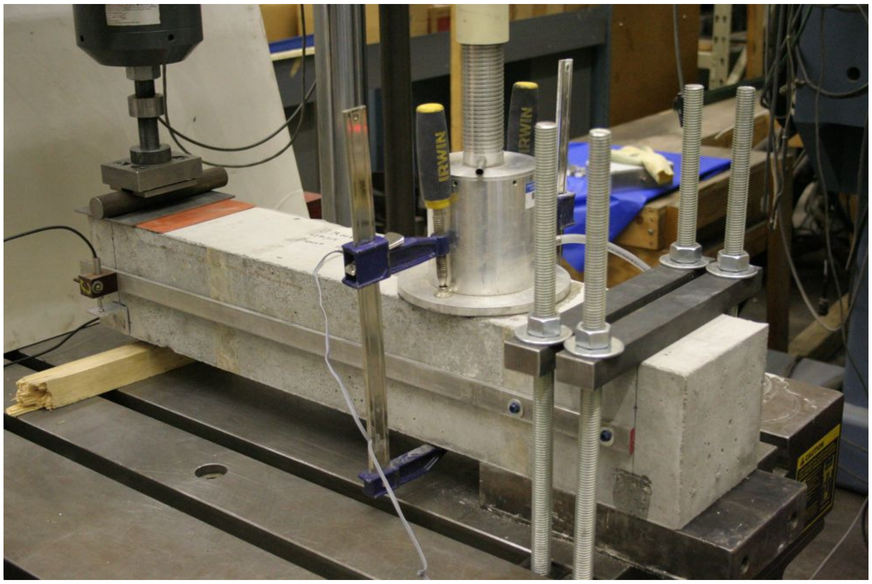

Figure 2. Cantilevered beam with the coring apparatus clamped on.

More than a dozen beams were tested with the core ring procedure. The general method started with a load cycle or two on the beam to characterize the beam’s stiffness and to ensure the strain gage was working properly. A load was then held for the duration of the coring to simulate a pavement with a constant stress state. The core rings were drilled in increments of 0.25 in to a total depth of 1.25 in. Drilling core rings disturbed the strain measurement, due to the heat generated from the drilling friction. The strain usually stabilized after about 10 to 15 minutes. The core rings were further deepened after waiting for the strain gage measurements to reasonably stabilize. The strain effects of drilling the core ring five times are clearly shown in Figure 3.

This figure also shows the other common characteristic of the coring tests, the strain decreases with deeper core rings. This is the strain relaxation the test was designed to create. Drilling the core ring near the strain gage reduces the stress in the concrete at the strain gage. This behavior also appears in Figure 4, where the strain is plotted against the load for the same beam for two cases: before the core ring was drilled and after it was drilled to its final depth. The strain versus load relationship is clearly changed by the core drilling. In both cases, the relationship is linear, but the slope decreases by about half after the core ring is drilled. The relationship also shifts down in strain after the drilling. Before drilling, the strain gage measured about 4 microstrain when unloaded; after drilling, the strain gage measured about -12 microstrain when unloaded, a 16 microstrain decrease. This is not an anomaly specific to this tested beam, the negative strain shift occurred in practically all of the tested beams. The shift shows that there are other stresses being relieved in the beams besides the cantilever loading. The beams’ self-weight does not change the strain measurements by nearly this much, so the conclusion is that these beams had their own residual stresses. Differential drying shrinkage is the likely stress source. The beams’ surfaces would dry and shrink more than the centers, creating tension stresses on the surfaces and compression stresses in the center. The tests results do indicate residual tensile surface stresses.

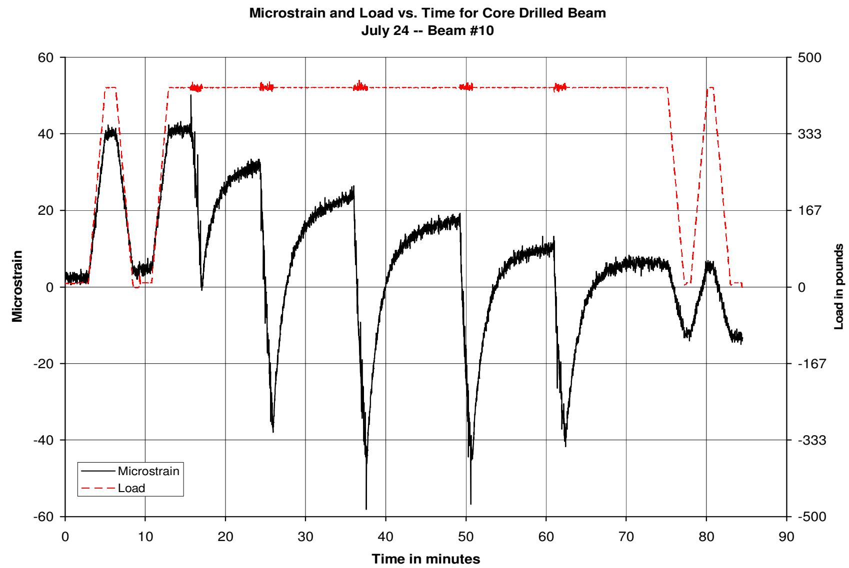

Figure 3. Characteristic core ring test results of the load and microstrain versus time. The center of the 30-mm strain gage was 1.45 in from the core ring edge.

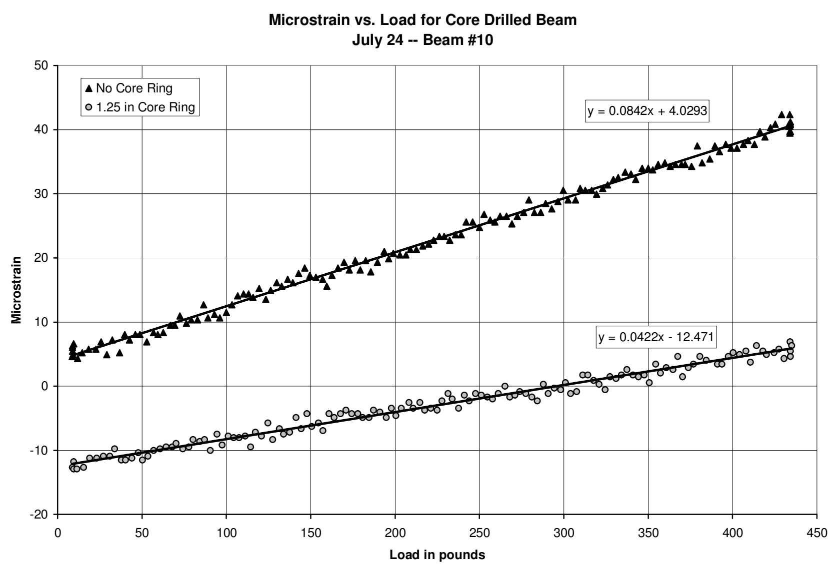

Figure 4. Characteristic microstrain versus load result plot for a beam before and after coring.

Two valuable conclusions arise from this discovery of shrinkage stresses in the beam specimens. The first is a reminder of how easily residual stresses can form in concrete. The second is a pleasant confirmation that this core ring strain gage test method can indeed measure residual stresses in concrete. However, measuring residual stresses in the beams was greatly facilitated by applying the external cantilever load, something that cannot be practiced easily for a pavement test. Also, many core ring test results did not come out as clearly as those shown in Figures 3 and 4. In many tests, the strain measurement drifted substantially after about an hour into testing. It is believed that the drifting was caused by the cooling water affecting the concrete and/or the strain gage. While reducing the use of the cooling water helped to reduce the drifting, a simple test on an already cored beam showed that the strain measurement was very sensitive to the cooling water temperature. The core ring test did demonstrate its ability to measure residual stresses, but the difficulties of the drifting strain measurements and the fact that only about half of the stress can be relaxed pushed the development of a different type of test using notches.

NOTCHED BEAM TESTS

The same beam geometry, strain gages, and cantilever setup were used for the notched beam tests. A hand-held electric circular saw was fitted with a masonry saw blade and was used to create the notches. The saw provided for a variable notch depth, though this adjustment was course, so a pair of calipers was used to verify the notch depths after each pass. Three common notch depths were used: 0.5, 1.0, 1.4 inches, the last one being the deepest possible notch for the equipment and setup. The sawing did not require cooling water, so the strain gages were not waterproofed. Wood spacers were placed over the strain gages as shown in Figure 5 to prevent the bottom of the saw from contacting the strain gage. The spacers also served as guides to place the notches in the desired locations.

The first round of notch tests used one notch on the side of the strain gage toward the applied load (a similar placement as the core ring tests). The results were very similar to the core ring data. The strain disturbance caused by sawing a notch took less than half the time to stabilize as in the core ring tests. This is most likely due to less heat generated by the faster notching procedure (about one minute per notch compared with five minutes per increase in core ring depth). The strain measurement did not drift like in some of the core ring tests.

The final testing phase of this project involved sawing notches on both sides of the strain gages; see Figure 6 for an image of two notches around a strain gage. The results were similar to the single notch tests, but with the strain relaxing much more with the two notches. Sawing notches close enough to the strain gage was able to completely relax the strain. Figure 7 shows a test where this occurred. Around minute 190 in that test, after the two notches had been sawn, changing the applied load to the end of the beam did not change the strain gage measurement. The strain versus load relationships, Figure 8, for that beam show this as a linear relationship with a near-zero slope. Note that the data from this beam test also shows a strong presence of residual stresses.

A test on an unloaded beam using the double notching procedure demonstrates the capability of this test. As shown in Figure 9, the residual strain becomes quite apparent with the notching. The strain approaches a stable level with the increase in notch depths.

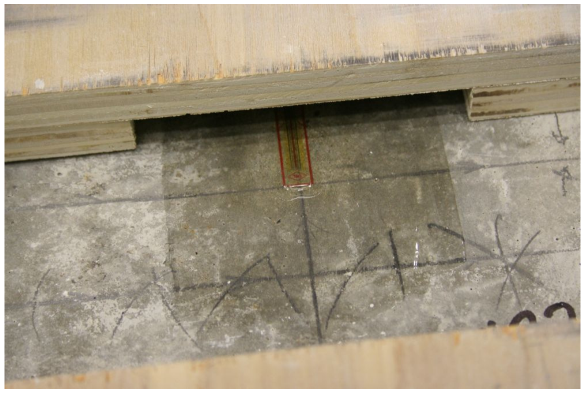

Figure 5. Wood spacers protected the strain gages from contact during the notch sawing.

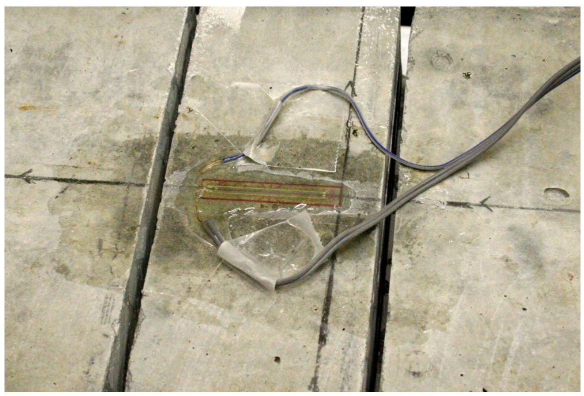

Figure 6. With careful installation of strain gages and their lead wires, notches can be sawn very close to each end of the gage.

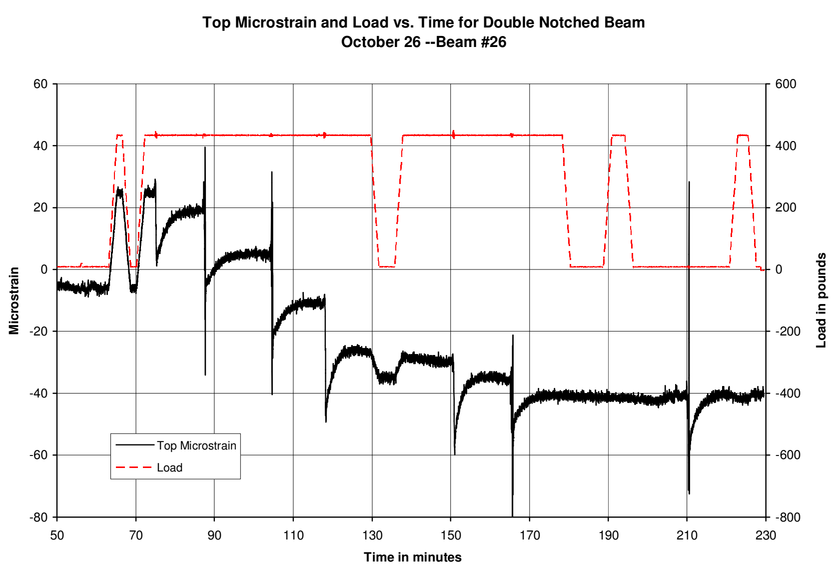

Figure 7. Strain and load data from a double notched beam. Two notches were sawn on either side of a 30-mm strain gage, about 1.7 in. from the notch edges to the gage center.

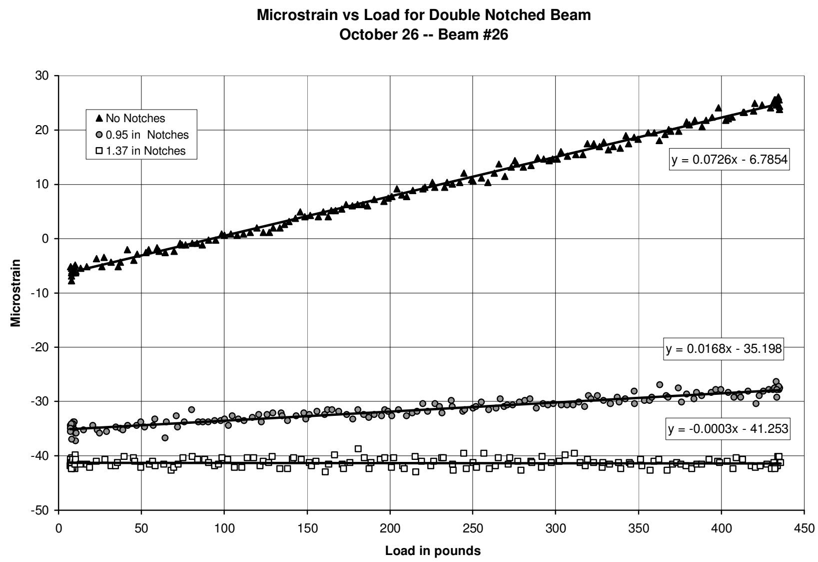

Figure 8. Microstrain and load relationships for a cantilevered beam with notches on both sides of the strain gage. When the notches are at the maximum depth, the strain gage measurement is fully isolated from the end loading.

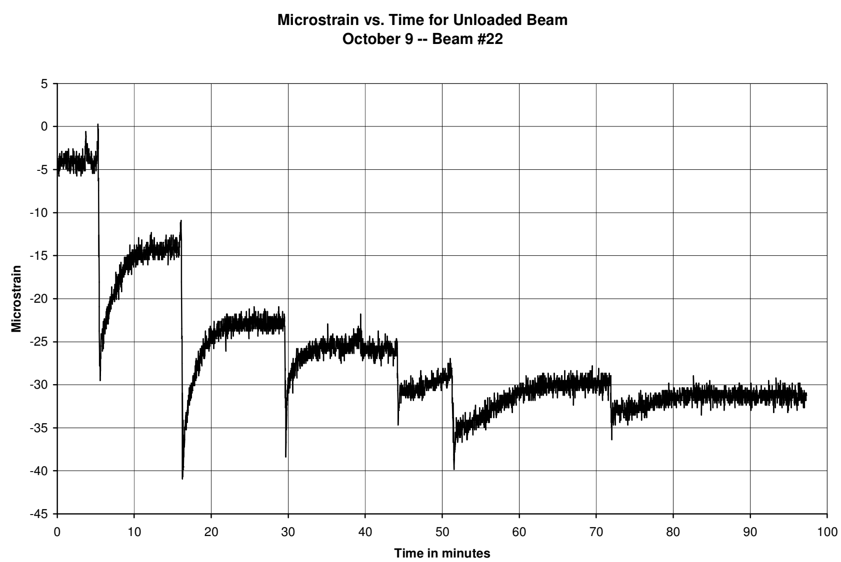

Figure 9. Strain results from sawing notches on both sides of a strain gage attached to an unloaded beam. The results show a residual surface strain of about 30 microstrain.

COMPARISON OF FINTE ELEMENT ANALYSIS WITH NOTCHING RESULTS

Cantilevered beams were modeled in finite elements to mimic the experimental test setup. The analysis used a two-dimensional model, a simplification made possible by the geometry of notching. Models were created for beams with one notch and beams with two notches. The single-notch beams were modeled having notch depths of 0.5, 1.0, and 1.5 inches. The double-notch beams were modeled having notch depths of 0.25, 0.5, 1.0, and 1.5 inches and spacing between the notches of 3.5 inches. Two more double-notch beams with notch spacing of 5 inches were modeled with depths of 1.0 and 1.5 inches. A plain beam model, without any notches, was also created for a reference. The fixities and loading of the models were designed to be similar to the laboratory restraints and load application.

For the single notch analysis results, the top surface stress values were used to estimate the strain that would be measured by a 30-mm strain gage (the size of strain gage used on all of the notched beams). The stress values were averaged over the strain gage length and were normalized to the stresses from the plain beam. A similar normalization was also performed with the single notch test data; this normalization was based between the estimated fully relaxed strain and the strain for the loaded beam before notching. Figure 10 plots the numerical and experimental results together. Although the finite element results were stress and the experimental results strain, normalizing them allows for a direct comparison assuming linear material behavior. This plot shows similar trends for both sets of data. The stress and strain relaxation is very dependent on distance from the notch. Full relaxation as indicated by zero on the vertical axis is possible if the strain gage is very close to the notch, with less relaxation further away.

Figure 11 plots the numerical and experimental results from the double notching tests. Using normalized values from the same procedures as before, the stress and strain relaxation is plotted against a geometric ratio of notch depths to spacing between the notches. This plot shows a fairly linear relationship with full relaxation occurring when the notch depths are about 40% of the spacing between the notches. It is notable that sawing notches deeper than this level shows an over relaxation of the strain—this is a result of the cantilever end load creating compressive stress and strain in the gage area.

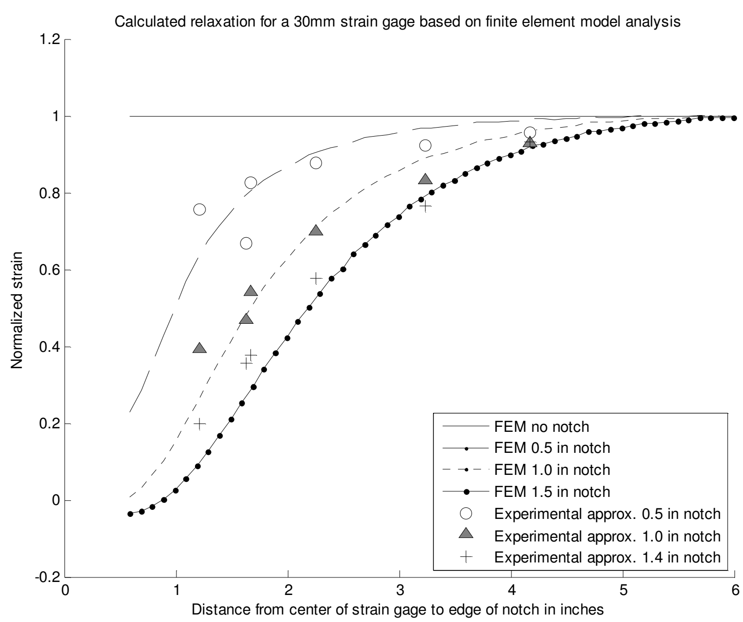

Figure 10. Finite element and experimental results for single notched beams.

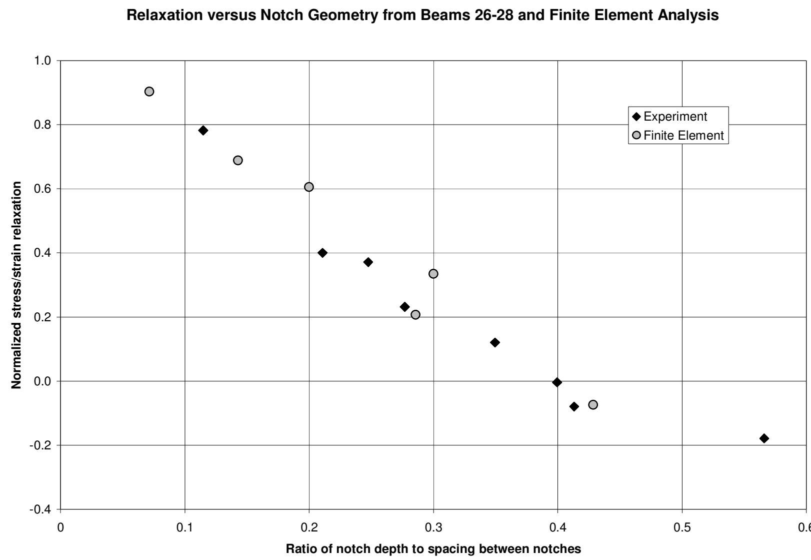

Figure 11. Stress and strain relaxation with respect to double notching geometry.

CONCLUSIONS

Measuring the strain change caused by drilling core rings or sawing notches in cantilevered concrete beams can be used to determine the residual stresses in the beams. Sawing notches is the more-effective method as its strain measurements are not influenced by cooling water use and by using two notches, the strain can be fully relaxed.

All of the results from this project are colored by stress distributions in cantilevered beams. Different stress distributions such as pure tension or compression and different geometry such as slabs may create different responses to the notching procedure, but the general ability of notches to fully isolate a strain gage is likely to remain. A notching procedure shows great promise as a test to determine the residual stress in pavement slabs.

ACKNOWLEDGEMENTS

Senior graduate students Jacob Henschen and Yi Shi Liu were great resources on concrete materials and on the ins and outs of laboratory work. Extra appreciation goes to Jacob for his idea to notch the beams instead of drilling core rings in them. Jacob, Yi Shi, David Gimeno, Daniel Castaneda, and Richard Santos all helped with making and testing the beam specimens.

Edward Guo, of SRA International, was invaluable for sharing his experience with his similar testing at the FAA’s NAPTF facility. He also gave many helpful comments about the progress of this project. The FAA’s David Brill and Frank Pecht also played roles in this project with project administration and laboratory testing experience, respectively.

Financial assistance for this project came from the Center of Excellence in Airport Technology (CEAT) with support from the Federal Aviation Administration and its work to study the performance of airport pavements.

REFERENCES

1. Lu, Jian, ed. Handbook of Measurement of Residual Stresses. Lilburn, GA: The Fairmont Press, 1996.
2. Guo, Edward H., Frank Pecht, Lia Ricalde, Donald Barbagallo, and Xinkai Li. "Data Analysis on Residual Stresses Measured in Concrete Beams." 9th International Conference on Concrete Pavements. San Francisco, CA. August 2008.